

Influence of measurement levels number on the accuracy of calculated estimate during the electrical energy measurements verification

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Abstract. Verification of electric energy measurement is a very important issue. The research deals with the modified method of testing equations, which enables measurement-based electrical energy estimation of higher accuracy compared to the initial measurements. The influence of the testing equations number on the estimation error value is investigated. Test results are presented for 14-node IEEE scheme. The necessity of using the limited measurement level number is proved.

1. Introduction

Information about the measured values of electrical energy received from Automatic Meter Reading (AMR) systems is generally quite reliable. Such systems use modern microprocessor-based electrical energy meters as well as reliable modern methods of measurements data retrieve, transmission and storage. Nevertheless, the possible failure of any system component will cause data errors or gaps, which are difficult to detect and eliminate. Mathematical approaches to measurements errors identification are the most promising and require the least financial investment [1, 2].

Current trend in electrical energy automated metering systems is their further technological advancement. Although the systems and their component devices become more and more technically complex, the actual electrical energy losses value remains high and significantly exceeds the technical and regulatory-specified values. Grid companies draw up the electrical energy balance monthly, with the balance serving as the basis for deriving the actual energy losses in order to compare them to the regulatory-specified ones. In case the commercial losses value is significant, the grid company suffers financial damage.

The causes of excessive commercial losses include underestimation of energy supplied to consumers, and intentional theft. The supplied energy underestimation is often driven by the instrument transformers overload. The AMR complex measurement error depends upon the feeder operation conditions and load with energy value typically being underestimated under off-nominal conditions. Hence, negative AMR complexes systematic errors might lead to commercial energy losses increase. Another issue is intentional commercial metering data distortion, especially in case the metering complexes are owned by consumers, who are interested in measurements understatement to decrease the electricity costs.



Commercial losses have been increasing during over the last 20 years, resulting in financial damage to energy exchange parties and grid companies, in particular. Commercial component of the overall energy losses doubles the expenses of transmission companies as they bear the financial responsibility. First, grid company receives less than due for energy transport because of commercial losses. And after that it pays for commercial losses during the actual energy losses covering procedure.

Commercial losses at 0.4 kV level are the most expensive for grid companies as energy transport rates corresponding to that level are the highest. Grid companies energy audit experience shows that the highest share of commercial losses corresponds to the low-voltage levels as well, which results in energy transport tariff increase, leading, in turn, to electricity cost rise for all end-users, especially for low-voltage ones.

Decreasing the commercial share of energy losses is possible through locating their sources, identifying the causes and eliminating them. Energy measurements verification enables locating the major commercial losses sources in the network [3]. In order to effectively establish the financial relations between market participants exact and reliable information about energy exchange is necessary. Since measurements in AMR systems are obtained at predefined regular intervals of time, it is possible to employ mathematical models and methodology to assess the system performance as well as verify and validate the commercial measurements on a real-time basis [4].

2. Energy measurements validation

State estimation theory, being widely used in power engineering to verify telemetry data [1, 2, 5], is characterized by high degree of scientific development [6–12]. Body of mathematics employed in state estimation solution includes fundamental steady-state equations along with computational optimization techniques.

Initial data in state estimation problem includes network diagram and its parameters; impedances and conductances in the diagram are assumed to be constant. The solution involves estimating the voltage magnitude and angle of each node and currents of all branches as well as nodes' active and reactive power injections.

A wide variety of crucial problems might be solved based on the obtained data: identifying the invalid measurement data and locating its source; estimating the parameters, that are not measured; assessing the measurement errors values and their statistical properties; obtaining the estimates of higher accuracy compared to the actual measurements. The approaches and methods, allowing to solve the listed problems, are well-developed and have found wide application in automated dispatch management systems algorithms. Hence, they might as well be adapted and applied to the challenge of bad data validation in electric energy measurements.

During previous research [13–15] the impossibility of employing the traditional steady state equations for energy flow calculation was shown and confirmed. Implementation of these equations leads to significant simulation errors. The problem of obtaining the energy flows and energy losses corresponding to all network elements based on energy measurements was named the Energy Flow problem. It was proposed to adopt the node and branch energy balance equations as energy flow state equations system:

$$\sum_{j \in \omega_i} W_{ij} + W_i = 0, \quad i = 1, 2, \dots, N; \quad (1)$$

$$W_{ij} + W_{ji} - \Delta W_{ij} = 0, \quad ij = 1, 2, \dots, M,$$

where W_i is the i node energy injection; W_{ij} is the i node connections energy flow; ω_i is the array of the nodes adjacent to the i node; N is the number of nodes in the network; M is the number of branches in the network. This approach has a lot in common with the traditional methodology of actual and admissible imbalances comparison.

3. Measurements estimated equivalents calculation, maximum admissible errors

Within the framework of state estimation theory the equations containing all measured variables are referred to as testing equations. The testing equations approach can be applied to energy measurements in energy flow problem [4, 17]. Testing equations system might be formed by excluding all parameters, which are not measured, from energy flow state equations system by any available mathematical means. Substitution of all measurements in case they could contain no errors into the testing equations system would lead to zero residual error. Therefore, the measurements errors drive non-zero residual error, while bad data results in significant residual error.

The number of testing equations determines the number of a single energy flow measurement levels. Thus, redundant measurements presence enables obtaining a range of estimated equivalents for the same variable. The estimate accuracy (maximum admissible error) can be derived according to

$$\delta_{W_i} = \sqrt{\sum_{j=1}^n a_j^2 \cdot \delta_{W_j}^2}, \quad (2)$$

where a_j is the coefficient of W_i in the i testing equations number. The less measurements are included into the corresponding TE the lower the estimate maximum admissible errors.

Figure 1 presents the possible levels of W_1 energy flow metering. The first stage is forming the energy flow state equation system. The number of equations equals three: two equations for node energy balances and one for branch balance. The second stage is obtaining the testing equations system, which implies elimination of all variables, that are not measured, from the state equations system. The network shown in figure 1 is characterized by full measurement coverage; hence, the testing equations system is entirely in accord with the energy flow state equation system. The third stage is constructing the verifying equations group out of the testing equations system. The estimated energy flow is to remain on the left side of the equation and the rest variables are transferred to the right part. Three testing equations allow to obtain three verifying equations for the estimated energy flow:

$$\begin{aligned} W_1 &= W_2, \\ W_1 &= W_3 - \Delta W, \\ W_1 &= W_4 + W_5 - \Delta W. \end{aligned} \quad (3)$$

Energy flow value here can be calculated based on the three levels of measurement, i.e. this energy flow is measured at three levels. Local redundancy coefficient [13] is calculated as the number of redundant measurements plus one. At least one measurement is required to provide observability for figure 1 diagram [16]. The number of measurements in considered example is four (measurements 4 and 5 form one node measurement).

Assuming the relative accuracy of all AMR complexes to be 1.6 % [18], the relative accuracy of measurement levels 1 and 2 is also 1.6 % according to (2). On the supposition that the technical losses calculation error is 10 % and the value of technical losses are about 1 % of the energy flow under normal operation conditions, the relative accuracy of technical losses calculation is 0.01 %. Therefore, the relative accuracy of the third and the forth levels measurements are, correspondingly, $\sqrt{1.6^2 + 0.01^2} \approx 1.603\%$ and $\sqrt{1.6^2 + 1.6^2 + 0.1^2} \approx 2.265\%$. The most accurate measurement estimated equivalent can be obtained by minimizing the relative measurement errors squares weighted sum:

$$F = \sum_{k=1}^{K_{red}} \frac{1}{(\delta_k \cdot W_k^{meas})^2} (W_k^{meas} - W^{est})^2 \rightarrow \min. \quad (4)$$

The summand number under the sum sign (4) equals K_{red} . δ_k values are calculated according to (2). The first factor $(\delta_k \cdot W_k)^{-2}$ in (4) corresponds to the relative accuracy of energy flow measurement. In case all the redundant measurements are the same, the function (4) can be reduced to a common denominator:

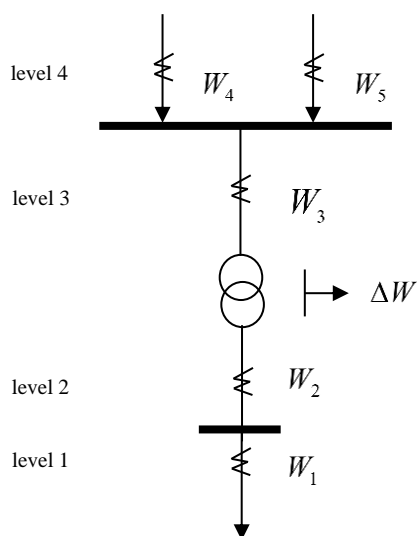


Figure 1. Measurements level

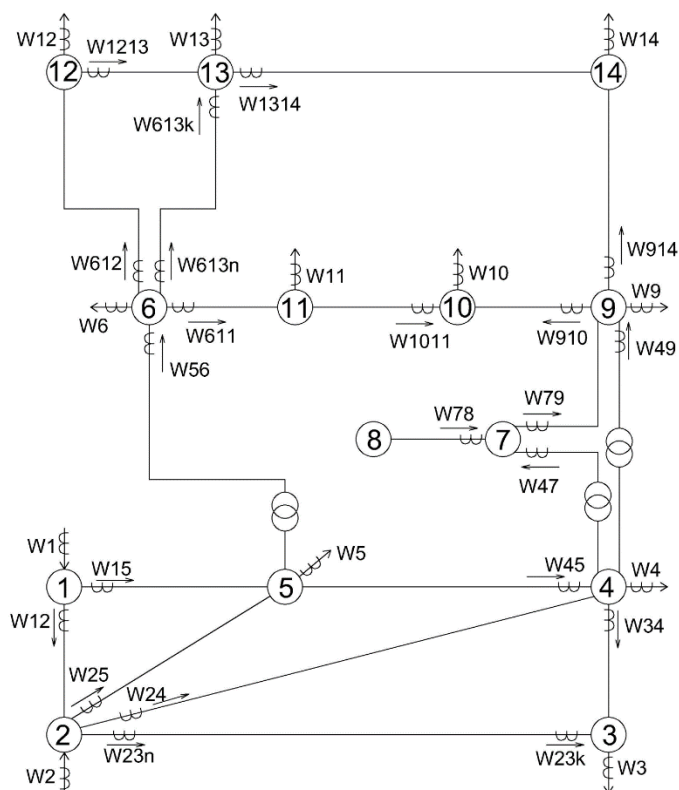


Figure 2. Considered test network.

$$F = \frac{\sum_{k=1}^{K_{ref}} \left(\prod_{k=2}^{K_{ref}} \delta_k^2 \right)}{\prod_{k=1}^{K_{ref}} \delta_k^2} \cdot \left(\frac{W^{est}}{W^{meas}} \right)^2 + C \quad (5)$$

The relative error of the energy flow measurement estimated equivalent based on the redundant measurements can be evaluated in accordance with

$$\delta_{est} = \left[\prod_{k=1}^{K_{red}} \delta_k^2 \cdot \left(\sum_{k=1}^{K_{red}} \prod_{k=2}^{K_{red}} \delta_k^2 \right)^{-1} \right]^{0.5}. \quad (6)$$

In the considered example the energy flow estimate relative error based on the remaining redundant measurements would be as low as $\delta_{w_i} \approx 0.856\%$. The resulting relative error of energy flow estimate is almost half as large as the AMR complex w_1 measurement relative error itself, assumed to be 1.6 %. If the technical losses calculation error is not taken into account, the estimate relative accuracy will be $\delta_{w_i} \approx 0.855\%$. In practice the technical losses calculation error can be as high as 20 % and even more. However, this level of the losses value uncertainty affects the estimation relative error insignificantly. In the considered network under the condition of 20 % losses calculation error, the estimation relative error is still 0.858 % and not more than 0.869 % even if the technical losses calculation error increases up to 50 %.

4. Test example, estimation of the measurement levels optimal number

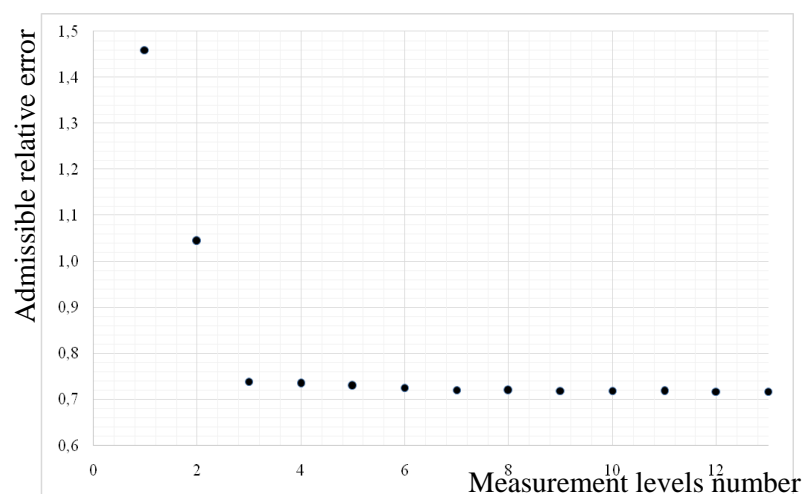
IEEE 14-node scheme presented in figure 2 is considered as a test example, it includes 110 kV and 220 kV voltage levels.

Table 1. Calculated estimates and verifying equations errors.

Parameter	Energy flow value, MW·h	Admissible error, MW·h	Admissible error, %	Estimate error, %
$W_1^{level(1)}$	17.879	0.26104	1.460	1.460
$W_1^{level(2)}$	18.237	0.190	1.044	1.044
$W_1^{level(3)}$	17.947	0.188	1.046	0.739
$W_1^{level(4)}$	16.705	1.069	6.399	0.734
$W_1^{level(5)}$	16.478	1.066	6.472	0.730
$W_1^{level(6)}$	16.310	1.067	6.540	0.725
$W_1^{level(7)}$	16.796	1.070	6.369	0.720
$W_1^{level(8)}$	17.611	2.668	15.147	0.720
$W_1^{level(9)}$	15.297	2.664	17.412	0.719
$W_1^{level(10)}$	15.632	2.765	17.685	0.718
$W_1^{level(11)}$	16.315	2.762	16.927	0.718
$W_1^{level(12)}$	14.567	3.640	24.990	0.717
$W_1^{level(13)}$	15.431	3.784	24.521	0.717

The installed AMR complexes are marked in simplified form by the windings of instrument transformers with reasonable measurement redundancy being provided. A variety of operation conditions was simulated employing RASTR software complex in order to obtain the resulting energy distribution. The relative measurement error limit of all AMR complexes installed is assumed to be 1.46 %, all measurements are assumed to correspond to that predefined error limit. Herein W_1 measurement is investigated; the verifying equations are formed for it. 13 measurement levels are considered.

Table 1 shows the w_1 energy flow estimates, MW·h, and admissible error values, MW·h and on a percentage base. The right column of table 1 gives the estimate admissible errors obtained on the basis of corresponding measurement levels number. It is convenient to illustrate the results as a plot of estimate admissible error against measurement levels number, as shown in figure 3. It is clear from the graph that the admissible error after level 4 slightly changes, hence it is sufficient to use level 5 for the case under consideration.

**Figure 3.** Admissible relative error as a function of measurement levels number.

5. Conclusion

Modern AMR systems are quite reliable sources of data comprising electrical energy flows corresponding to network elements. However, any system component fault or malfunction might result in significant measurement errors or bad data occurrence. Mathematical approach to identifying those issues is the least demanding in financial terms. State estimation theory methodology adapted to fit the energy flow problem requirements enables successfully addressing the issue of electrical energy measurements verification. Testing equations method modification allows obtaining energy measurements estimated equivalents, admissible errors of which are lower than of the initial measurements. Herein, the technical energy losses evaluation error influences the estimation accuracy insignificantly. Provided four measurement levels, the estimate error is decreased twice compared to the error of the measurement itself. Thus, the estimate accuracy depends upon measurement redundancy: the number of redundant measurements determines the testing equations number and the estimate admissible error value. However, involved measurement levels number increase influences the computational burden and equations system complexity. The optimum measurement levels number for the test case under considered conditions equals five.

6. References

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